

Solar cycle variations in the growth and decay of sunspot groups

J. Javaraiah¹

Abstract We analysed the combined Greenwich (1874–1976) and Solar Optical Observatories Network (1977–2011) data on sunspot groups. The daily rate of change of the area of a spot group is computed using the differences between the epochs of the spot group observation on any two consecutive days during its life-time and between the corrected whole spot areas of the spot group at these epochs. Positive/negative value of the daily rate of change of the area of a spot group represents the growth/decay rate of the spot group. We found that the total amounts of growth and decay of spot groups whose life times ≥ 2 days in a given time interval (say one-year) well correlate to the amount of activity in the same interval. We have also found that there exists a reasonably good correlation and an approximate linear relationship between the logarithmic values of the decay rate and area of the spot group at the first day of the corresponding consecutive days, largely suggesting that a large/small area (magnetic flux) decreases in a faster/slower rate. There exists a long-term variation (about 90-year) in the slope of the linear relationship. The solar cycle variation in the decay of spot groups may have a strong relationship with the corresponding variations in solar energetic phenomena such as solar flare activity. The decay of spot groups may also substantially contribute to the coherence relationship between the total solar irradiance and the solar activity variations.

Keywords Sun: Dynamo – Sun: surface magnetism – Sun: activity – Sun: sunspots – (Sun:) solar-terrestrial relations

1 Introduction

Solar activity affects us in many ways. Flares and coronal mass ejections pose a serious hazard to astronauts, satellites, polar air-traffic, electric power grids and telecommunications facilities on short time-scales ranging from hours to days. The solar radiative output affects planetary and global climate on much longer time-scales (from decades to stellar evolutionary time-scales). The study of variations in solar activity is important for understanding the underlying mechanism of solar activity and for predicting the level of activity in view of the activity impact on space weather and global climate (Hathaway 2009).

Recently, (Javaraiah 2011a, hereafter Paper-1), using the combined Greenwich (May/1874 to 1976) and Solar Optical Observatories Network (1977–2009) data on sunspot groups, we studied the long-term variations in the daily mean percentage growth and decay rates of sunspot groups. Two of the main results found from this study are: (i) From the beginning of Cycle 23 the growth rate is substantially decreased and near the end (2007–2008) the growth rate is lowest in the past about 100 years. (ii) In the extended part (beyond the length of the declining part of a normal cycle) of the declining phase of this cycle, the decay rate steeply increased and it is largest in the beginning of the current Cycle 24. These unusual properties of the growth and the decay rates during Cycle 23 may be related to cause of the very long declining phase of this cycle with the unusually deep and prolonged current minimum. However, no significant correlation was found either between spot group growth rate and sunspot number or between the latter and spot group decay rate. The patterns of variations in the growth and decay rates are found to be considerably different in different cycles. In fact, the mean percentage growth rate of the spot groups in the declining phases of some cycles is found to be considerably large and the mean percentage decay rate of the

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spot groups in the rising phases of some cycles is found to be considerably large (see Fig. 6 in Paper-1). In the present paper we showed that the annual amounts of growth and decay of spot groups well correlated to the annual amount of activity and discussed the implications of this result on the solar cycle variation of the solar energetic phenomena such as solar flares and that of the total solar irradiance (TSI). We have also studied the dependence of the growth and decay rates of the spot groups on their sizes. Such a study may help for understanding the underlying mechanism of the emergence/growth and decay of magnetic flux.

In the next section we describe the methodology and the data analysis. In Section 3 we present the results. In Section 4 we draw conclusions and briefly discuss the implications of them.

2 Methodology and data analysis

Here we have used the combined Greenwich (May/1874 to December/1976) and Solar Optical Observation Network (SOON) (January/1977 to May/2011) sunspot group data, which are taken from David Hathaway's website, <http://solarscience.msfc.nasa.gov/greenwich.shtml>. These data included the observation time (the Greenwich data contain the date with the fraction of the day, in the SOON data the fraction is rounded to 0.5 day), heliographic latitude and longitude, central meridian distance (CMD), and corrected umbra and whole-spot areas (in millionth of solar hemisphere, msh), etc., of the spot groups for each day of observation. The positions of the groups are geometrical positions of the centers of the groups. In case of SOON data, we increased area by a factor of 1.4. David Hathaway found this correction was necessary to have a combined homogeneous Greenwich and SOON data (see aforementioned web-site of David Hathaway). The area of a spot (or spot group) is closely connected with the magnetic flux of the spot (or spot group). The 130 msh area $\approx 10^{22}$ Mx magnetic flux (*e.g.*, see Wang & Sheeley 1989).

The data reduction and analysis are similar as described in Paper-1. A brief descriptions of them is given here (for details see Paper-1). We have taken all the precautions which were taken in Paper-1. We have used the corrected daily whole-spot areas (umbral value + penumbral value) of spot groups (A). A spot group is included when the observations of it are available for two or more consecutive days. The spot groups having the group numbers with suffix A, B, etc., which are available in the SOON data for some years, are not used in this analysis. However, they are few and many of them found to have zeros for values A . The

daily rate of change of the area ($\frac{\Delta A}{\Delta t}$) of a spot group is computed using the differences between the epochs of its observation in consecutive days and between the corrected whole spot areas of the spot group at these epochs. That is,

$$\frac{\Delta A}{\Delta t} = \frac{A_n - A_{n-1}}{t_n - t_{n-1}}, \quad (1)$$

where t is the epoch of observation during the life-time (T) of the spot group and $n = 2, 3, \dots, T$. The data correspond to only $0.5 < \Delta t < 2$ day are used. Positive and negative values of $\frac{\Delta A}{\Delta t}$ correspond to the daily rates of growth (G) and decay (D) of the spot group, respectively, i.e.,

$$\frac{\Delta A}{\Delta t} = \begin{cases} > 0 & = G, \\ < 0 & = D. \end{cases} \quad (2a) \quad (2b)$$

The sums S_G and S_D of G and D , *i.e.* the total amounts of growth and decay of the spot groups in a given time interval, are determined as follows:

$$S_G = \sum G_i \text{ and } S_D = \sum D_j, \quad (3)$$

where $i = 1, 2, \dots, k$ and $j = 1, 2, \dots, m$; k and m are the number of data points of G and D , respectively, in the interval. We also determined the sum of the areas of spot groups (S_A) in corresponding time interval, $S_A = \sum A_l$, *i.e.*, the annual sum of A , where $l = 1, 2, \dots, N$. N includes all reliable data points (including those correspond to the spot groups which had born and dead within one day, which are available in Greenwich data).

We determined the annual S_G and S_D and their correlations with annual S_A . Obviously more contributions to S_G and S_D are coming from the spot groups before and after reaching their maximum areas, respectively (see Fig. 1 in Paper-1). It should be noted here S_A and S_D not only did not include the corresponding contributions of other activity phenomena, they even did not include the corresponding contributions of one-day groups. Therefore, they do not represent the amounts of complete growth and decay of magnetic activity in a given time interval.

To check whether the growth and decay rates of the spot groups depend on the sizes of the spot groups we determined the correlations and the linear/quadratic list-square fit to logarithmic values of $G_{n-1,n}$ and $|D_{n-1,n}|$, which are derived from A_{n-1} and A_n , and corresponding A_{n-1} in a given time interval (it should be noted that the values of n are different for the growth and decay rates). The statistical significances of the

Table 1 Values (in msh day^{-1}) of cycle S_G , S_D and S_A (in msh) and the corresponding number of data points k , m , and N , respectively.

Year	S_G	k	S_D	m	S_A	N	Year	S_G	k	S_D	m	S_A	N
1874 ^a	7704	101	-10401	185	110848	410	1943	10559	140	-8958	205	100054	450
1875	5796	85	-7008	146	71824	376	1944	3790	106	-4454	130	41732	335
1876	4109	57	-5128	121	37802	256	1945	14531	287	-15558	450	142271	1008
1877	1925	48	-2591	87	30574	218	1946	52065	816	-55259	1193	613676	2617
1878	917	18	-1041	37	7753	76	1947	93043	1293	-80703	1808	880814	3961
1879	1447	35	-1664	48	12711	114	1948	64320	1099	-71321	1621	660406	3555
1880	16301	225	-14819	275	148066	713	1949	73716	1153	-71714	1665	709618	3618
1881	23403	384	-28231	582	233877	1349	1950	39326	652	-40250	999	410458	2133
1882	32410	497	-37242	666	322272	1518	1951	31605	487	-33303	817	383792	1712
1883	35147	509	-41690	770	392421	1678	1952	10865	221	-15038	439	136097	884
1884	35357	620	-30821	873	348129	1904	1953	3698	92	-6301	198	48729	399
1885	23591	452	-26822	661	272557	1438	1954	2466	40	-1466	56	11528	154
1886	10435	228	-10716	302	124279	692	1955	15708	292	-20003	523	188297	1102
1887	4534	104	-6385	217	58856	423	1956	74858	1033	-75226	1625	805335	3495
1888	2034	59	-3676	126	30458	254	1957	92087	1347	-97049	2025	1030795	4519
1889	2420	61	-2002	81	26031	181	1958	104359	1456	-107399	2132	1016484	4649
1890	3680	61	-4633	103	33662	245	1959	85162	1272	-86205	1927	966043	4178
1891	20571	344	-18502	518	182676	1147	1960	52810	947	-56159	1339	543777	2994
1892	35153	611	-42382	970	400948	2163	1961	22120	428	-22192	630	205291	1474
1893	45905	831	-51331	1366	489336	2877	1962	12848	278	-16083	436	149997	944
1894	40539	723	-44901	1197	426001	2544	1963	8981	209	-10188	322	94727	749
1895	31791	546	-30944	907	327530	1992	1964	3039	98	-2354	139	17462	359
1896	19073	337	-19692	493	179861	1105	1965	5326	130	-5271	206	38028	473
1897	11089	241	-12251	369	164355	850	1966	24612	409	-21802	553	198533	1377
1898	10413	182	-12889	353	127138	729	1967	54784	920	-51612	1269	511008	3149
1899	3557	90	-5251	192	38288	371	1968	44987	775	-52904	1235	525099	2748
1900	3573	76	-3971	122	24558	260	1969	46869	781	-46647	1262	489365	2745
1901	962	21	-1150	35	9695	72	1970	51669	941	-51765	1359	527659	3112
1902	3014	33	-2297	54	20794	128	1971	27523	572	-30248	951	329595	2063
1903	7485	163	-11062	316	111170	703	1972	25923	609	-34400	938	302052	2111
1904	18531	373	-20863	543	163222	1285	1973	13521	288	-16506	496	151689	1111
1905	28320	507	-35503	778	399858	1812	1974	16077	298	-13854	407	130523	1012
1906	26295	497	-25688	723	255142	1731	1975	6249	122	-5548	157	56883	440
1907	30918	524	-30768	781	358190	1810	1976	5063	125	-5381	162	54738	394
1908	22080	458	-19575	666	228713	1568	1977	14471	216	-15379	240	116909	862
1909	22123	413	-21320	589	231773	1349	1978	52217	761	-54128	1141	471536	3701
1910	9187	210	-9264	324	88160	723	1979	85123	1172	-85067	1649	753027	5025
1911	1964	79	-3276	123	21043	263	1980	77175	945	-72511	1219	736414	3672
1912	2203	50	-1497	54	12676	146	1981	81318	972	-77640	1243	777174	3645
1913	347	15	-466	22	2683	60	1982	78540	815	-79842	1119	756462	3072
1914	4810	107	-5555	165	51100	408	1983	36456	482	-35434	662	318990	2069
1915	21391	456	-23446	685	235067	1738	1984	25998	293	-25746	414	274008	1263
1916	27793	585	-27313	881	237122	2138	1985	7350	95	-7868	161	61432	502
1917	52994	982	-51555	1437	515459	3266	1986	4732	76	-5264	104	41160	347
1918	38390	766	-39210	1177	365995	2689	1987	9716	171	-10808	244	100296	793
1919	30157	588	-31948	941	349358	2082	1988	43022	560	-45724	778	464660	2453
1920	18914	343	-19174	578	202831	1289	1989	86744	921	-90216	1308	885234	3935
1921	13040	234	-12999	376	137361	869	1990	71932	948	-72744	1304	700798	3926
1922	8947	141	-8697	227	81593	501	1991	77476	898	-80710	1311	843920	3840
1923	2381	54	-2900	104	19981	239	1992	50960	630	-46186	858	460789	2470
1924	8167	142	-9089	248	90535	543	1993	23436	374	-21490	442	235760	1274
1925	29665	460	-25162	692	280126	1600	1994	11942	214	-11228	281	115262	836
1926	31973	584	-36563	914	420728	2062	1995	7420	130	-7966	187	54502	492
1927	37578	621	-35608	1007	355199	2194	1996	4564	55	-3108	64	27972	217
1928	38609	661	-44095	1114	459454	2399	1997	9702	140	-7602	160	71022	534
1929	36813	639	-39030	1014	414790	2244	1998	30044	419	-23450	483	258972	1568
1930	16662	367	-20441	590	172294	1295	1999	46578	629	-37016	727	393680	2236
1931	11866	204	-10740	303	89798	712	2000	60830	870	-53970	1029	544936	2991
1932	5189	120	-4309	177	52896	434	2001	57722	856	-53794	1081	578474	3040
1933	1930	63	-3292	93	29935	211	2002	66318	898	-59583	1110	620455	3134
1934	3158	81	-4404	137	38006	308	2003	41055	544	-36260	719	372722	1910
1935	22155	359	-19788	531	208639	1189	2004	25410	344	-23849	427	230916	1153
1936	41495	719	-42964	1079	386772	2500	2005	20244	241	-18200	332	180222	864
1937	68489	1024	-63853	1538	700115	3491	2006	8680	135	-7615	186	84127	538
1938	55398	872	-57529	1440	676297	3154	2007	3430	60	-5124	97	46088	282
1939	50506	821	-53038	1233	535160	2693	2008	1246	26	-1456	42	7805	111
1940	38560	612	-35387	873	348600	1947	2009	2044	33	-910	24	9058	115
1941	23683	396	-23130	620	223784	1384	2010	8644	148	-8428	169	72804	528
1942	16901	295	-16763	426	144345	939	2011 ^a	10129	136	-7868	126	73178	471

^aindicates data are available only for about half years in the cases of 1874 and 2011.

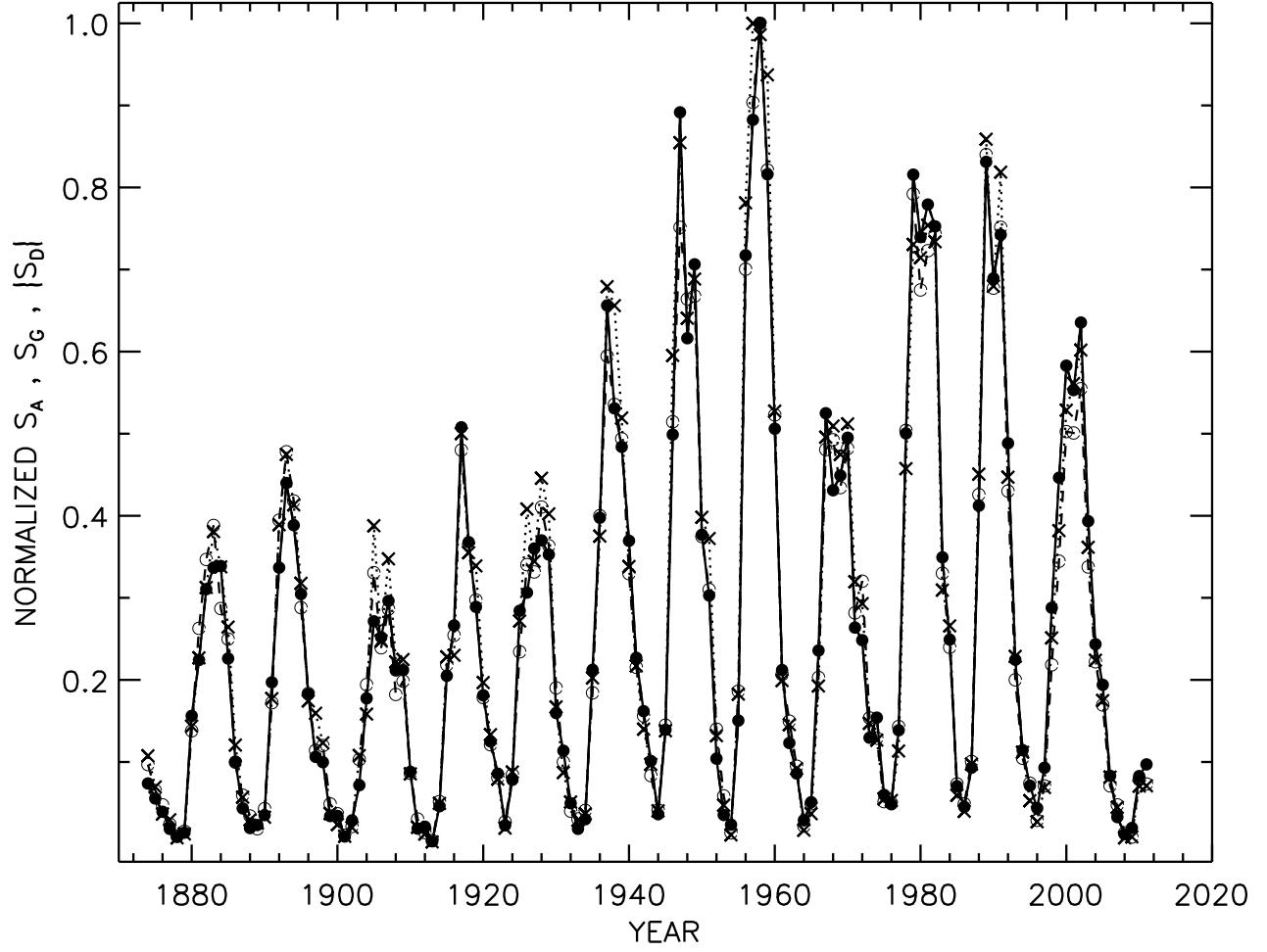


Fig. 1 Plots of normalized annual sum of daily area (S_A , cross-dotted curve), annual amounts of growth (S_G , filled circle-solid curve) and decay (S_D , open circle-dashed curve) of spot groups *versus* year. The S_A , S_G and S_D are normalized with their respective maximum values (cf., Table 1)

regression relations and the values of correlation coefficients are tested using χ^2 and Student's 't' distributions, F-test, standard error and z-transformation tests (Yule & Kendall 1958).

area. Fig. 2 shows the correlations between S_G and S_A and between $|S_D|$ and S_A (all these are divided by 10^4). These correlations, correlation coefficients $r = 0.989$ and $r = 0.994$, are very high (significant on > 99.9 confidence level). The slopes of the corresponding lin-

3 Results

3.1 $S_G - S_A$ and $S_D - S_A$ relations

In Table 1 we have given the annual values of S_G , S_D and S_A . Fig. 1 shows the plots of the normalized annual values of S_A , S_G and $|S_D|$ *versus* year. It may be worth to note here that in cycle 23 S_A has maximum at year 2002. The maximum of the international sunspot number (not shown here) is at 2000. Recently, Ramesh (2010) found that the maximum of coronal mass ejection (CME) is close to that of the sunspot

ear relationships are almost equal $(0.097 \pm 0.001)^{-1}$ and are statistically highly significant (**the values of Student's 't' are found to high, i.e. the values of their corresponding probabilities are found be close to one**). These relations suggest that a larger amount of growth or decay is associated with a larger amount of activity. That is, the amounts of growth and decay of the flux in a given time interval depends on (proportional to) the total amount of flux in that interval. Obviously the amounts of growth and decay of magnetic flux is larger during the maximum epochs than during minimum epochs. During Maunder minimum S_A was very low/absent. Hence, S_G and S_D were also very low/absent.

3.2 Decay law

Howard (1992) analysed Mt. Wilson sunspot and sunspot group data during the period 1917–1985 and found that the daily percentage umbral areas increases for small groups are larger in absolute terms than the percentage umbral areas decreases, and for large groups the daily percentage decreases are larger than increases. Fig. 3 shows the dependence of the decay rate, $|D_{n-1,n}|$, of a spot group determined from A_{n-1} and A_n i.e., the areas at $(n-1)$ th and n th days during the life time of the spot group, on A_{n-1} . In this figure the continuous and dashed curves represent the corresponding linear and quadratic fits. The values of the intercept and the slope of the linear fit ² are 0.26 ± 0.02

¹The $S_A - S_G$ and $S_A - S_D$ relations can be written as follows:

$$\frac{S_A}{S_G} \approx \frac{S_A}{S_D} \approx 10 \text{ day.} \quad (4)$$

It is well believed that large spot groups also live long. In fact, there is a rule of the proportionality of the maximum area (A^0) of a sunspot group to its life-time (T) (first plotted by Gnevyshev, 1938; and formulated by Waldmeier, 1955; see also Petrovay & Van Driel-Getztelyi, 1997):

$$\frac{A^0}{T} \approx 10 \text{ msh day}^{-1}. \quad (5)$$

Incidentally, the right hand sides of (4) and (5) have a value approximately equal to ten, but their units differ (the unit of former is day, whereas the unit of the latter is msh day⁻¹). They seem to be independent relations. The (5) represents the average property of a whole individual spot group (it may not applicable to the growth and the decay portions of the spot groups, independently), whereas the (4) represents largely a global property of the solar cycles.

²It is a power-law, $|D_{n-1,n}| \approx e^{0.26} A_{n-1}^{0.613}$, suggesting that decay of spot group do not completely depend linearly on the size of the group. It should be noted that the linear decay law is widely accepted as only a simplest approximation (see Petrovay & Van Driel-Getztelyi 1997).

and 0.613 ± 0.002 , respectively. Since the number of data points, $m = 88490$, over the whole period from May/1874 to May/2011 is are very high, the levels of the statistical significances of the values of the coefficients of both the linear and the quadratic fits (whose values are not given here) are very high. The χ^2 value of both the linear and the quadratic fits are found to be insignificant at 5% level. The χ^2 value (68386) of the quadratic fit is found to be slightly less than that (68649) of the linear fit. However, the F-test indicated that no significant difference in the variances of these fits. The correlation between $|D_{n-1,n}|$ and A_{n-1} is high ($r = 0.65$) and statistically very significant (i.e., it is about 19 times larger than its standard error ($\approx \frac{1}{\sqrt{m}}$), and it is also found to significant in z-transform test). This and the linear (or quadratic) relations indicate that a large/small flux decays in a faster/slower rate. This is consistent with the $S_A - S_D$ relation above.

In order to check the consistency of the aforementioned analysis for small data samples and dependence (if any) of the above found relationship on the solar cycle, we analysed the data of individual cycles and also yearly data as well as binning the data into 3-year moving time intervals (3-MTIs) successively shifted by one-year. In Fig. 4, we show the cycle-to-cycle variation in the slope of the linear relation between $\ln(|D_{n-1,n}|)$ and $\ln(A_{n-1})$ derived from the individual cycles' the whole sphere (disk) data, and also separately from the northern and southern hemispheres' data, of spot groups during each of the cycles, 12–23. In the same figure we have also shown the variation in the amplitudes of the same cycles (the maximum monthly mean international sunspot numbers which are taken from the website, ftp://ftp.ngdc.noaa.gov/STP/Solar_DATA/SUNSPOT_NUMBERS). In each cycle the values of the coefficients of both the linear and quadratic laws as well as the value of the correlation coefficient are found to be statistically significant and the F-tests suggest that no significant differences in the variances of the linear and quadratic fits. The ranges of the correlation coefficient (and of the ranges of the corresponding number of data points, i.e., m values) are 0.592–0.608 (4547–11113), 0.582–0.596 (2033–6388), and 0.599–0.609 (2514–4725) determined from the whole sphere, northern hemisphere and southern hemispheres' data, respectively, during the cycles 12–23. In Fig. 4 it can be seen that the slope varies on a long-time scale of about 90-year, with amplitude of about 0.02 unit. **The variation in each hemisphere is very closely resemble to that of the whole sphere. There is a suggestion that in a large number of cycles the slope is steeper in the northern hemisphere than in the southern hemisphere. However, only in cycles 16 and**

21 the differences between the values of the northern and southern hemispheres are somewhat large and statistically significant. Fig. 5 shows the relationship between $|D_{n-1,n}|$ and A_{n-1} in Cycle 16. The patterns of these relations are closely resemble to that derived from for the whole 138 year data (cf., Fig. 3). The aforementioned difference in the slopes between northern and southern hemisphere during Cycles 16 and 21, i.e., in a gap of about 5 cycles, may be related to a 44–55 year cycle in solar activity (Yoshimura & Kambry 1993; Javaraiah 2008).

The value (it is only 0.08) of the coefficient of the correlation between the sunspot activity (amplitude of the cycle) and the slope is found to be negligible. During the 90-year cycle (Gleissberg cycle) in the sunspot activity there are many relatively small time-scale strong fluctuations, whereas there are no such fluctuations during the 90-year cycle in the slope. However, there is a close agreement in the epochs of the maxima and the minima of these cycles of the slope and the cycle amplitude (the phase shift between these is not clear in Fig. 4). This may suggest the existence of a relationship between the long-term variations in the slope and the sunspot activity.

Fig. 6 shows the variations in the slope and the correlation coefficient determined from the data in 3-year MTIs 1874–1876, 1875–1877, ..., 2009–2011. In order to check the solar cycles trends in these parameters, in this figure we have also shown the variation in the international sunspot number smoothed by taking 3-year running average. Only a few of these values of the slopes shown in this figure are statistically insignificant. That is, in many intervals the values of χ^2 are found to be insignificant at 5% level, and the Student's 't' tests suggest that the significant levels of the corresponding values of the correlation coefficient are also good (Note: the big jump of the correlation coefficient from the interval 1977 to 1978 (the high values from 1978 onward) could be just an artifact of the multiplication of the area values of the SOON data with 1.4, in order to have a continuous and homogeneous data for the whole period 1874–2011 (cf., Sec. 2). As can be seen Fig. 6(a) the values of the slopes are considerably low near the declining ends of small cycles (12, 16 and 23), particularly in the end of Cycle 23 the slope is smallest in the last about 100 years (which may be related to the unusually low and prolonged recent activity minimum). The long-term (90-year cycle) variation seen in the cycle-to-cycle variation (Fig. 4) can also be seen in Fig. 6(a). We have used the 3-MTIs for the sake of better statistics, but the aforementioned patterns is also seen in the yearly data (figure is not shown here), in spite of the large uncertainties in the yearly values.

We would like to point out that the statistical significances of all the regression relations are tested by Student's 't' tests also. In all the cases the values of 't' are found to be high, i.e., the values of their corresponding probabilities are found to be close to one (for example, the interval 2008–2010 has the smallest number of data points $N = 163$. In this case the value of 't' is found to be 7.375, whereas the cutoff value for the five percent significance level is only 1.654 and for one percent level it is 2.35).

Fig. 7 shows the plots of the mean slope values in 3-MTIs—i.e., the data shown in Fig. 6(a)—versus the year of the solar cycles, 11–24 (data are available only for four years of Cycle 11 and only for 3 years of Cycle 24). As can be seen in this figure, the pattern of the mean variation of the slope (the closed circle-solid curve) suggests a slight increasing trend during the rising phases and a slight decreasing trend during the decay phases of a majority of the solar cycles. However, the overall spread in the data points is very large, particularly in the beginnings and the endings of the cycles. That is, the variations during the different solar cycles highly differ from the mean pattern, indicating the ≈ 11 -year periodicity is very weak/absent in the slope.

Overall we find that the relationship $|D_{n-1,n}|$ and A_{n-1} is reasonably consistent and reliable even in the cases of the relatively small samples. It may be worth to note here that the average size of the spot groups considerably varies during a cycle. It also differs from cycle-to-cycle. Therefore, the temporal variation in the slope of the linear relationship may be mainly due to the dependence of the decay rate on the size/lifetime of the spot groups.

We repeated all the above calculations for growth rate. The correlation between the growth rate, $G_{n-1,n}$, and the corresponding A_{n-1} is found to be low, $r = 0.39$, for the whole period data (with 60087 points). But it is still found to be statistically significant from the above used all the significance tests (it should be noted that the values of n is different for the growth and decay rates). However, the correlation determined from the data of an individual cycle is found to be still small and statistically insignificant. Thus, the relationship between $G_{n-1,n}$ and A_{n-1} is considerably inconsistent. Hence, it is not shown here. There is also a considerable spread in Figs. 3 and 4. Therefore, even the relationship between $|D_{n-1,n}|$ and A_{n-1} found above, is only suggestive rather than compelling.

4 Conclusions and discussion

We analysed a large and reliable sunspot group data and found that the total amounts of growth and decay

of spot groups whose life times ≥ 2 days in a given time interval (say one-year) well correlate to the amount of activity in the same interval. We have also found that there exist a reasonably good correlation and an approximate linear relationship between the logarithmic values of the decay rate and area of the spot group at the first day of the corresponding consecutive days, largely suggesting that a large/small area (magnetic flux) decreases in a faster/slower rate. There exists a long-term (about 90-year) variation in the slope of this relationship.

The growth of spot groups (enhancement of magnetic flux) may have a large contribution from the emergence of new magnetic flux. Hence, the growth of spot groups may be mostly related to the generation mechanism of solar activity, whereas for the decay process magnetic reconnection may be the main mechanism. Magnetic reconnection is believed to be the main mechanism behind the solar energetic phenomena such as the solar flares, coronal mass ejection, etc.. Thus, the solar cycle variation in the decay of spot groups may have significant roles in the corresponding variations in the solar energetic phenomena, particularly solar flares which are mainly originate at sunspot locations.

The relationship (4) (see foot note of the $S_G - S_A$ and $S_D - S_A$ relations in Sec. 3.1) largely implies a change in the topology of surface magnetic flux in every 10 days, which is consistent with the following results/inferences: Howard & LaBonte (1981) analysed Mt. Wilson magnetograph data during the period 1967 to mid-1980 and found that the rate at which the magnetic flux appears on the Sun is sufficient to create all the flux that is seen at the solar surface within a period of about 10 days. The magnetic structures of the sunspot groups may rise from near the bottom of the convection zone to the surface in about 10 days (Javaraiah & Gokhale 1997). In addition, a ≈ 10 -day periodicity seems to be predominantly present in the solar surface differential rotation, total solar irradiance (TSI), solar coronal holes, solar wind, auroral electron power, and geomagnetic parameters (see Javaraiah 2011b, and references therein), all these may be related to the topology of the Sun's surface magnetic field.

It is known that TSI varies by about 0.1% over the solar cycle. A number of statistical models of TSI variability have been constructed on the basis of inhomogeneities of surface magnetic field. These models helped to identify the surface magnetic structures are responsible for the variation of TSI and also provided widely accepted theoretical explanations. According to these

models, the dominant part of the TSI variations on time scales longer than about a day is caused by the evolution of solar surface magnetic features. However, the exact mechanism behind the TSI variation is not known (Foukal 1992; Kuhn 1999; Solanki et al. 2005; Domingo et al. 2009).

TSI is well correlating with the solar activity (for example with sunspot number) and during the current unusually low and prolonged minimum TSI also seems to be unusually low (Fröhlich 2009). Sunspots and faculae act in opposite to modulate TSI (Lean 1988; Krivova et al. 2011). That is, sunspots depress the solar energy output, whereas faculae enhance it. However, the exact reason for the correlation between solar activity and TSI is not yet known.

The growth and decay of sunspot groups play key roles in the TSI variations (Wilson et al. 1981). The growth of spot groups may enhance the blocking of the energy output. The decay may enhance the energy output and mostly responsible for TSI to correlate with sunspot activity, *i.e.*, for the coherent relationship between the activity and TSI variations. Besides the convection, the meridional flows may play significant roles in the magnetic reconnection, hence in the decay of spot groups (in general all kinds of active regions).

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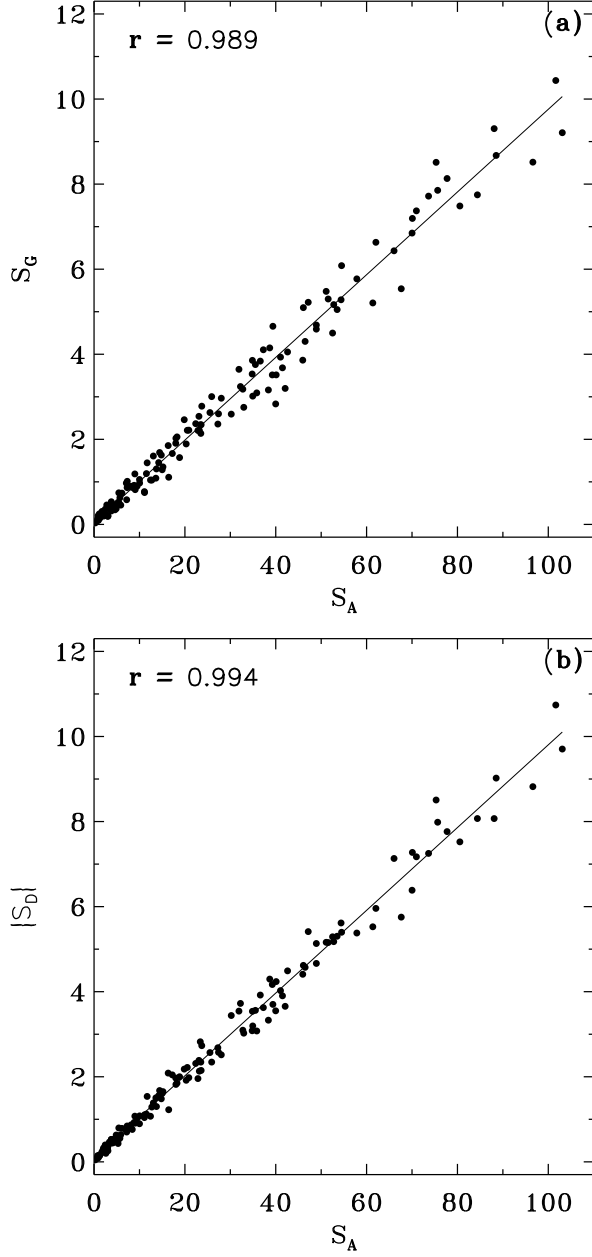


Fig. 2 Scatter plots of the annual S_A and $|S_D|$ versus S_A (the values which are given in Table 1 and divided by 10^4). The Solid line represents the corresponding linear relationship and the value of the corresponding correlation coefficient (r) is also shown

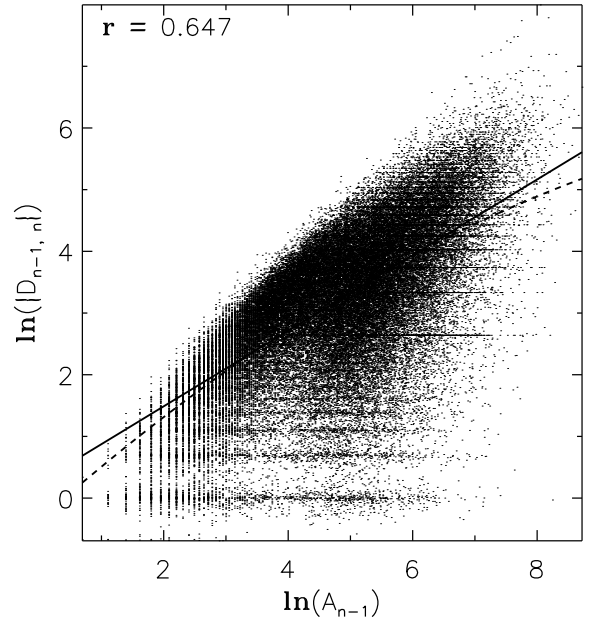


Fig. 3 Plot of $\ln(|D_{n-1,n}|)$ versus $\ln(A_{n-1})$. $D_{n-1,n}$ and A_{n-1} (cf., 1 and 2) are determined from the data during the whole period 1874–2011 (it should be noted that the values of n is different for the growth and decay rates). The continuous and dashed curves represent the corresponding linear and quadratic fits, receptively

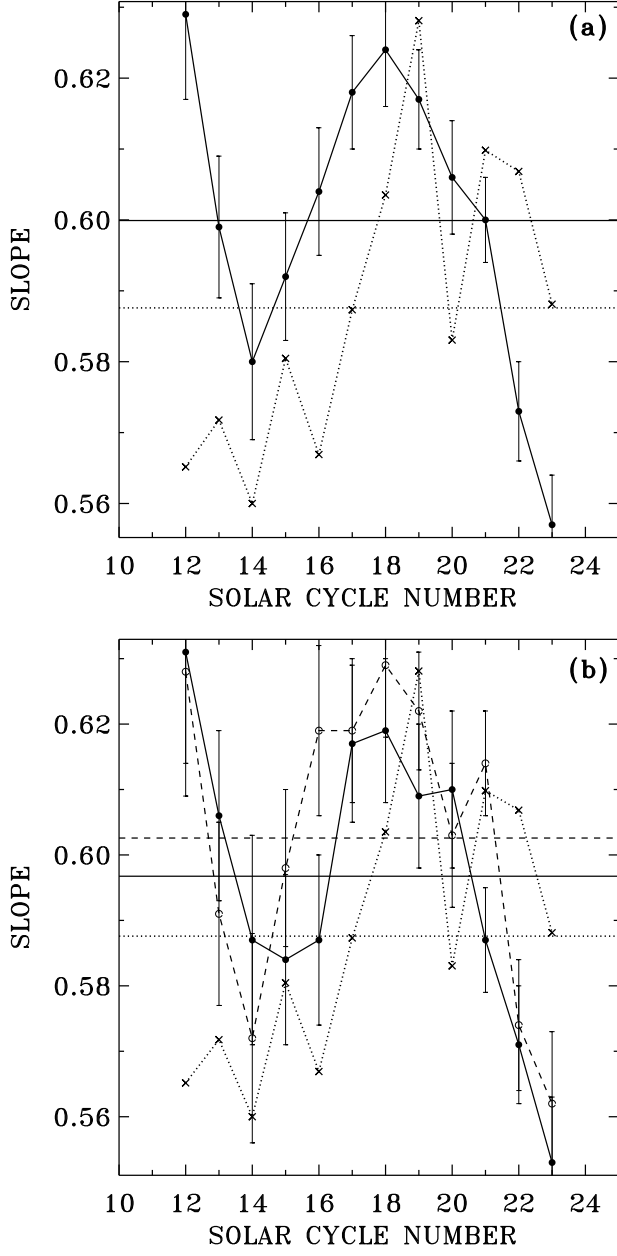


Fig. 4 Plots of cycle-to-cycle variation in the slope of the linear relationships between $\ln(|D_{n-1,n}|)$ versus $\ln(A_{n-1})$ derived from the data of spot groups in the whole sphere (upper panel) and in the different hemispheres (lower panel): northern hemisphere (open circle-dashed curve) and southern hemisphere (closed circle-solid curve). The cross-dotted curve represents the variation in the amplitudes of the sunspot cycles 12–23 (normalized to the scale of the slope). The corresponding values of the mean (over all cycles) are indicated by the horizontal lines of the receptive type

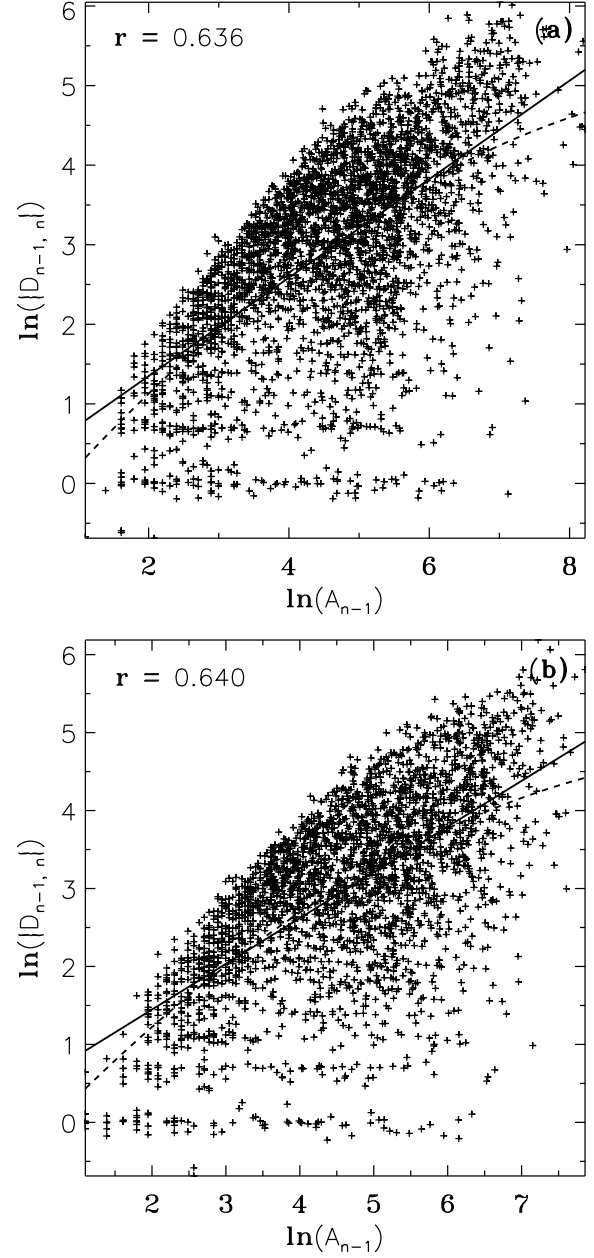


Fig. 5 The same as Figure 3, but determined separately from the data of the spot groups in the northern (upper panel) and southern (lower panel) hemispheres during Cycle 16 only

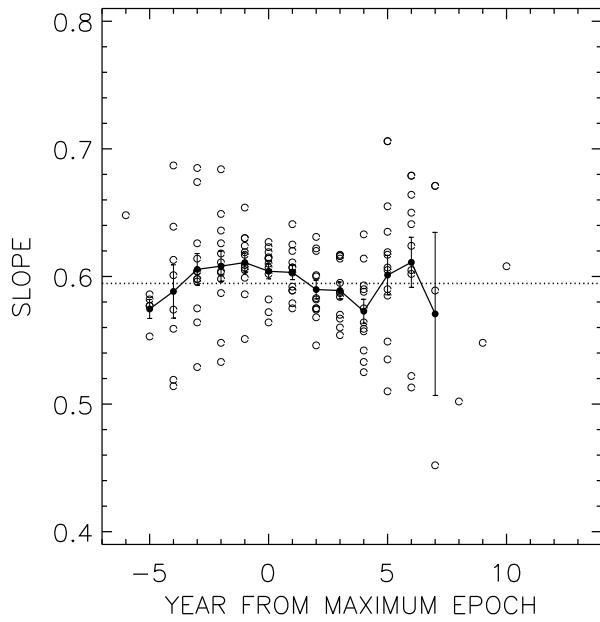


Fig. 7 Plots of the mean slope values in 3-MTIs, i.e., the data shown in Fig. 6(a), versus the year of the solar cycles, 11–24. The filled-circle-continuous curve represents the mean solar cycle variation determined from the mean values in 3-MTIs. The error bar represents the standard error. There are only one data point at years -6 (begin of Cycle 14), 8 (end of Cycle 23) and 9–10 (begin of Cycle 24)

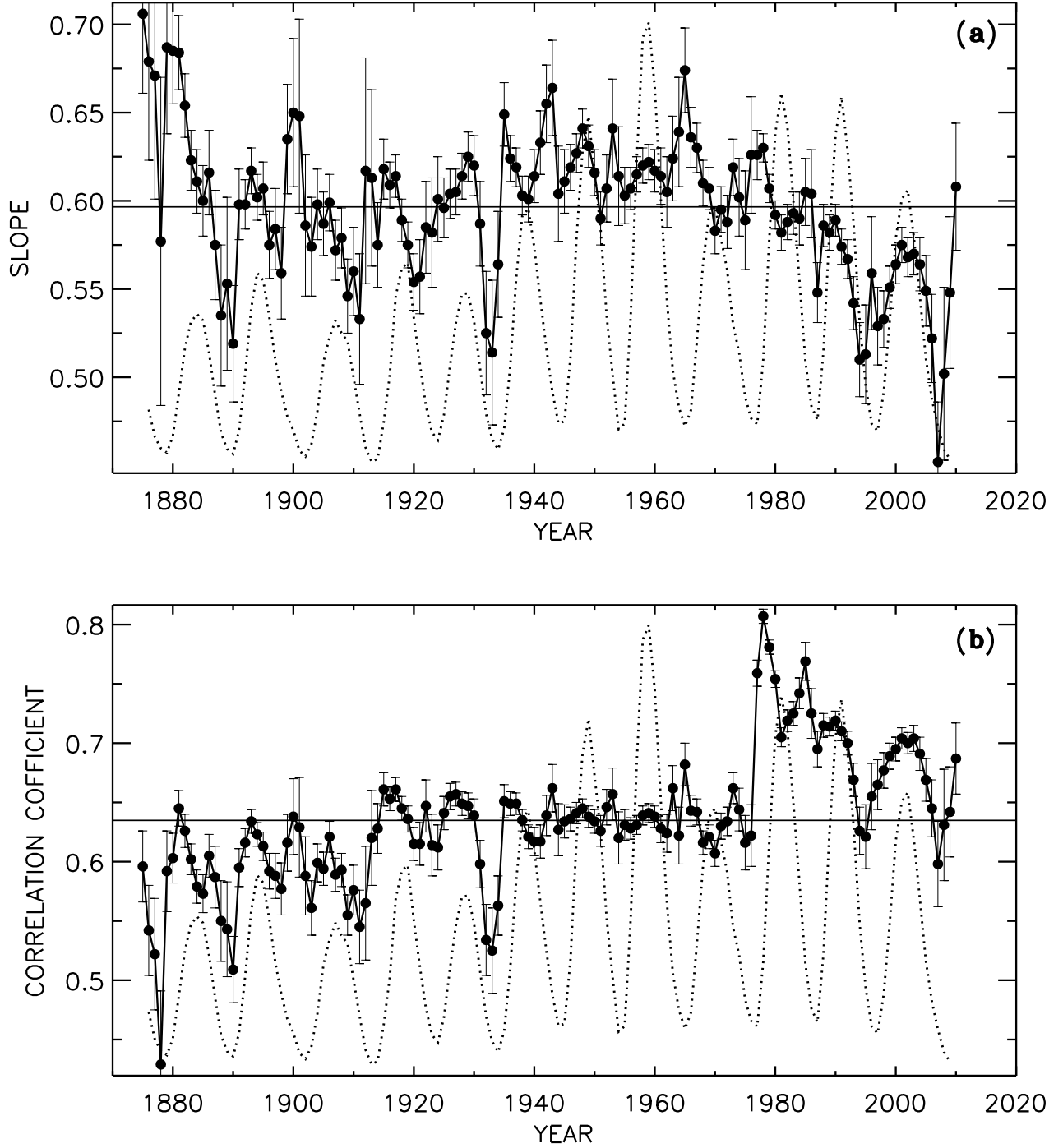


Fig. 6 Plots of the variations in the slope (upper panel) of the linear relationship between $\ln(|D_{n-1,n}|)$ and $\ln(A_{n-1})$, and the corresponding correlation coefficient (lower panel), derived from the whole sphere spot group data in 3-year MTIs 1874–1876, 1875–1877, ..., 2009–2011, *versus* the middle year of the interval. The dotted curve represents the variation in the yearly international sunspot number during 1874–2009, smoothed by taking 3-year running average (normalized to the scales of the slope and the correlation coefficient). The mean values of the slope and the correlation coefficient, over the whole duration, are indicated by the horizontal solid lines.

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